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AFCRL-62-957

INVESTIGATION OF HOT ELECTRON EMITTER

-hp associates-
2900 Park Boulevard
Palo Alto, California

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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
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ABSTRACT

Analysis is presented of the frequency performance of various metal-base hot carrier triode amplifiers which differ only in the type of hot carrier emitter they utilize. The triodes considered are: (1) The SMS, or semiconductor-metal-semiconductor, triode utilizing a Schottky barrier emitter; (2) The space charge limited emitter triode; and (3) The tunnel-emitter triode. The results are compared with the performance of the bipolar germanium junction transistor. It is shown that for all three hot carrier triodes, the maximum gain-band product increases with current density and approaches an assymptotic limit of about $1.4 \times 10^8/S$ which is due to collector limitation, where S is the stripe width in cm. It is further shown, however, that this limit is closely approached at reasonable current density only by the SMS triode. This limit is to be compared with a value of $(5 \text{ to } 12)10^6/S$ for the germanium transistor.

At an emitter current density of 1000 amp/cm^2 and a stripe width of 10 microns, the maximum gain-band products, or maximum oscillating frequencies, are 60 kmc/sec for the SMS triode, 38 for the space charge limited emitter triode, and 10 for the tunnel-emitter triode.

I INTRODUCTION

Considerable interest has been recently generated in solid state triode amplifiers based on hot carrier transport in thin metal films. Various structures have been proposed[1-4] and evidence of hot carrier triode action has been demonstrated.[3,5,6] Furthermore, independent measurements of transport of hot carriers in various metal films have been carried out[7], indicating ranges as high as several hundred Angstroms in the one electron volt energy range.

Three main hot carrier triode structures have been proposed. These are listed in Table I, together with other more conventional triode amplifiers. The basic operation of the three hot carrier triodes indicated is essentially the same. They differ, however, in one all-important respect, namely, the structure of the emitter and the mechanism of hot carrier injection into the metal base. The consequences of utilizing the various emitters indicated, on the overall amplifier characteristics, and particularly its high frequency limitations, are developed and presented in this report. Comparisons are also made with the performance of the more conventional bipolar transistor.

II COMPARISON OF TRIODES

II.1 Mechanisms of Operation

Figure 1 is a schematic presentation of the energy band diagram for each of the triodes compared. Diagram 1 represents a conventional npn transistor. Diagram 2 represents a tunnel emitter hot electron triode. Hot electrons are injected into

TABLE I

SOME PROPOSED OR EXISTING TRIODE AMPLIFIERS

I	Bipolar Transistors	(1) npn or pnp
II	Unipolar Transistors	(2) Field effect transistor (a) junction transistors (b) surface transistors (3) Analogue transistor
III	Hot Carrier Triodes	(4) Tunnel emitter triode (5) Space charge limited emitter triode (6) (SMS) Schottky emitter triode

the metal base by quantum mechanical tunneling through a thin insulating layer "W". Hot electrons transported across the metal base without collision are collected by passing over a lower energy base-collector barrier into the space charge of the reverse biased collector. Diagram 3 represents a hot electron triode with space charge limited emitter. Hot electrons are injected into the metal base by flowing from a metal (extreme left) into the conduction band of an insulating film "W" (or high resistivity semiconductor) and finally into the metal base. The electron flow in the emitter region "W" in this case is determined by the space charge of the flowing electrons. Diagram 3 represents the SMS or semiconductor-metal-semiconductor hot electron triode. The emitter is essentially a Schottky-type barrier which is so chosen that in forward bias, current flow is primarily due to majority carriers in the semiconductor (in this case electrons). This current will flow into the metal base as hot electrons.

II.2 Basic Emitter Characteristics

The emitter characteristics pertinent to our discussion are the capacitance-voltage and current density-voltage characteristics under forward bias. These are summarized in Table II.

The assumptions and notations used are as follows:

(1) For the npn transistor emitter, the emitter junction is a step $n^{+}p$ junction of unity injection efficiency. The base region

TABLE II

COMPARISON OF BASIC EMITTER CHARACTERISTICS*

Triode	Capacitance (C_e) - Voltage (U)	Current Density (j_e) - Voltage (U)
(1) npn Transistor	$C_e = \left[\frac{qN_b}{\frac{8\pi}{\kappa}(V_b - U)}\right]^{1/2}$	$j_e = q\frac{n_i^2}{N_b} \cdot \frac{D_n}{W_b}\left(e^{q\frac{U}{kT}} - 1\right)$
(2) Tunnel Emitter Triode	$C_e = \frac{\kappa}{4\pi} \cdot \frac{1}{W_e}$	$j_e = 1.54 \times 10^{-6}\left(\frac{1}{\phi}\right)\left(\frac{U}{W_e}\right)^2 \times \exp\left[-\frac{6.82 \times 10^7 \, \phi^{3/2}}{(U/W_e)}\right]$
(3) Space Charge Limited Emitter Triode	$C_e = \frac{3\kappa}{8\pi} \cdot \frac{1}{W_e}$	** $j_e = \frac{9}{32\pi} \kappa \mu U^2 / W_e^3$
(4) SMS Triode	$C_e = \left[\frac{qN_e}{\frac{8\pi}{\kappa}\left(V_b - \frac{kT}{q} - U\right)}\right]^{1/2}$	$j_e = qv_o N_e e^{-q\frac{V_b}{kT}}\left[e^{q\frac{U}{kT}} - 1\right]$

*All equations are in esu except where noted.

**Units are amp, volt, cm.

W_b wide and is a concentration N_b. A unity base transport factor is assumed. q is the electron charge, V_b is the barrier height, U is the applied forward bias, κ is the semiconductor dielectric constant, n_i is its intrinsic carrier density and D_n is the diffusion coefficient of electrons in the base region. (2) For the tunnel-emitter triode, it is assumed that current flow obeys a Fowler-Nordhiem relation of field emission or tunneling through a triangular potential barrier.[8] W_e is the thickness of the insulating emitter film through which tunneling occurs, ϕ is the metal-insulator barrier height, and κ is the insulator's dielectric constant. The numerical constants given correspond to T = 300°K. (3) For the space charge limited emitter, it is assumed that the emitter region W_e is free of fixed charges or traps and only a single carrier is present. It is also assumed that throughout the region the carrier velocity equals μE where μ and E are the carrier mobility and electric field, respectively. (4) For the SMS triode, the emitter barrier efficiency is unity (i.e., no minority carriers are injected into the semiconductor), the emitter is uniformly doped to a concentration N_e, the barrier height is V_b and v_o is the electron thermal velocity $(kT/2\pi m)^{1/2}$ in the semiconductor.

II.3 Emitter Conductance

Based on the relations given in Table II, the emitter conductance $g_m = (dj_e/dU_e)$ was calculated for each triode at different current densities. The results are shown in Figure 2

as g_m versus emitter current density. It is se en that the transistor and the SMS triode have the highest emitter conductances due to their strong exponential dependence of emitter current on voltage. The tunnel-emitter triode follows with intermediate values of g_m and finally the space charge limited emitter triode with the lowest emitter conductance due to its weak current-voltage dependence ($j_e \propto U^2$). At 1000 amp/cm^2 emitter current density, the respective values of g_m at 300°K are:

SMS	40,000 mho/cm^2
Transistor	40,000
Tunnel-Emitter Triode (κ_e=4, W_e=20Å)	12,000
Space Charge Limited Emitter Triode (κ_e=10, μ=200 cm^2/v.sec.,W_e=10^{-4}cm)	900

II.4 Emitter Figure-of-Merit g_m/C_e

For the four triode structures under consideration, comparisons were made of their emitter figure-of-merit g_m/C_e, which is the reciprocal of the emitter charging time τ_e. The results are given in Figure 3 as g_m/C_e versus emitter current density. The calculations were carried out at the specific conditions indicated at the top of Figure 3. It is to be noted that here again both the SMS triode and the transistor have essentially the same emitter performance as expected, both having the highest figures-of-merit. They are followed by the space charge limited emitter triode and finally by the tunnel-

emitter triode which exhibits the most serious emitter limitation. It should be further pointed out for the case of the tunnel emitter that for given emitter current density, an increase in emitter width W_e will not change its g_m/C_e since the resulting decrease in emitter capacitance is offset by a proportionate decrease in g_m (as can be readily verified from the relations in Table II).

At 1000 amp/cm^2 emitter current density, the figures-of-merit g_m/C_e for the various emitters are as follows:

SMS	2.2×10^{11} cps
Transistor	1.7×10^{11}
Space Charge Limited Emitter Triode	6×10^{10}
Tunnel-Emitter Triode	4×10^{9}

II.5 Triode Amplifier Gain-Band Product Figure-of-Merit

We will now compare the frequency performance of the triodes under consideration. A convenient form of gain-band product expression[9] is

$$K \equiv (\text{Power Gain})^{1/2}(\text{Bandwidth}) = f_{max.osc.}$$

$$= \frac{\alpha}{4\pi}\left[\frac{1}{r_b' C_c A \tau_{ec}}\right]^{1/2} \qquad (1)$$

where, α is the triode current transport ratio, r_b' is the base resistance, $C_c A_c$ is the collector capacitance, and τ_{ec} is the emitter-to-collector signal delay time. τ_{ec} is the sum of three terms: (1) the emitter charging time $\tau_{ec} = C_e/g_m$, where

g_m and C_e are the emitter conductance and capacitance per unit area, respectively; (2) the base transit time $\tau_b = \frac{W_b}{v_{th.m.}}$, where W_b is the metal base width, and $v_{th.m.}$ is the velocity of hot electrons in the metal; and (3) the collector transit time $\tau_c = \frac{X_m}{2v_{sc.lim.}}$, where X_m is the width of the collector depletion region, and $v_{sc.lim.}$ is the scatter limiting drfit velocity of the carrier in the collector.

For all three hot electron triodes considered, the base transit time is small and can be generally neglected (for $W_b = 10^{-6}$cm, and $v_{th.m.} = 10^8$cm/sec., $\tau_b = 10^{-14}$ sec.). Hence

$$\tau_{ec} = [C_e/g_m + \frac{X_m}{2v_{sc.lim.}}] \tag{2}$$

The dependence of gain-band product K on base width W_b is, therefore, only through the dependence of α and r_b' on W_b.

Following Early's treatment of the bipolar junction triode,[10] consider a simple linear stripe geometry of unit length with an emitter stripe width s, spaced s/2 from the base stripes. The collector capacitance is then sC_c, and the base resistance $r_b' = \frac{2}{3} s\rho_m/W_b$; where C_c is the collector capacitance per unit area $[= \frac{\kappa}{4\pi} \cdot \frac{1}{X_m}]$, and ρ_m is the resistivity of the metal base.

For a hot electron triode with unity emitter efficiency, its gain is given by:

$$\alpha = (1-R)e^{-W_b/L} \tag{3}$$

where L is the hot electron range in the metal base, and R is its reflection coefficient at the collector. Substituting for r_b', C_cA_c, and α in Equation (1), gives:

$$K = \frac{1-R}{4\pi s}\left(\frac{3}{2\rho_m C_c \tau_{ec}}\right)^{1/2} \cdot \left(W_b^{\;1/2} \cdot e^{-\frac{W_b}{L}}\right) \qquad (4$$

K, obviously, has a <u>maximum</u> which is reached when $W_b = L/2$, i.e., when the base width is just one half the hot electron range:

$$K_{max} = \frac{1-R}{8\pi s}\left(\frac{\frac{3}{e}\,L}{\rho_m C_c \tau_{ec}}\right)^{1/2} \qquad (5$$

Substituting for τ_{ec} from Equation (2) gives:

$$K_{max} = \frac{1-R}{s}\left[\frac{\frac{3}{8\pi e}\cdot L/\kappa\rho_m}{\frac{1}{v_{sc.lim.}} + \frac{2}{X_m(g_m/C_e)}}\right]^{1/2} \qquad (6$$

This relation is applicable to all three hot electron triodes under consideration. It indicates the dependence of K_{max} on the figure-of-merit (g_m/C_e) of the specific type of emitter which the triode utilizes. From the dependence of (g_m/C_e) on emitter current density j_e, as discussed in Section II.4 and presented in Figure 3, and from Equation (6) one obtains the dependence of K_{max} on emitter current density. This calculation was carried out and the results are given in Figure 4 as K_{max} versus emitter current density for the three hot electron triodes

under consideration. For comparison, Early's value of gain-band product of $\frac{(5 \text{ to } 12)\times 10^6}{s}$ for the bipolar germanium transistor is also indicated on the figure.

From the results, the following conclusions may be made: (1) The highest frequency performance should be obtainable by the SMS triode followed by the space charge limited emitter triode and finally by the tunnel-emitter triode. (2) While both the SMS triode and the space charge limited emitter triode have high frequency performances superior to that of the bipolar transistor, the tunnel-emitter triode performance will not exceed that of the bipolar transistor except at rather excessive emitter current densities. (3) For all three hot electron triodes, K_{max} approaches an assymptotic limit with current density which is due to collector limitations. As shown in Figure 4, however, only the SMS triode closely approaches this limit at a reasonable current density. This limit is readily obtainable from Equation (6) by setting $g_m/C_e = \infty$. Under the conditions of Figure 4, one obtains:

$$(K_{max})_{assym.} \quad \frac{1.4\times 10^8}{s(cm)} \text{ cps} \tag{7}$$

which is one to two orders of magnitude higher than calculated for the bipolar transistor.[10]

Finally, at an emitter current density of 1000 amp/cm^2, the maximum oscillating frequencies for the triodes under consideration are as follows:

SMS triode	60 kmc/sec.
Space Charge Limited Emitter Triode	38
Tunnel-Emitter Triode	10
(Bipolar transistor	5 to 12)

III PERSONNEL

Individuals who contributed to the contract activity in this report period are:

M. M. Atalla

R. W. Soshea

R. C. Lucas

C. H. Fox

D. A. Reid

V. M. Dowler

IV VISITORS, CONFERENCES AND TRAVEL

Visitors

There were no visitors to our Laboratory during this report period.

Conferences

Dr. M. M. Atalla presented a paper entitled "The Hot Electron Triode with Semiconductor Metal Emitter" at the 1962 NEREM Conference held November 5, 6 and 7 at Boston, Massachusetts.

Travel

Dr. M. M. Atalla visited the AFCRC Laboratories on November 8, 1962 to discuss contract progress with Mr. R. F. Cornelissen's group.

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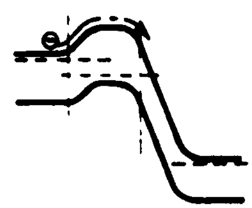
FIGURE CAPTIONS

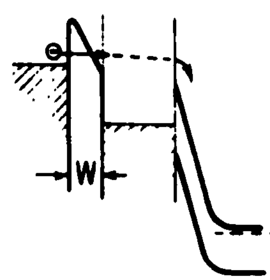
1. Schematic energy band diagrams for a bipolar transistor and three hot electron metal-base triode amplifiers.
2. Comparison of emitter conductance versus emitter current density for various triodes.
3. Comparison of emitter figures-of-merit versus emitter current density for various triodes (g_m/C_e is the reciprocal of the emitter charging time).
4. Comparison of gain-band product versus emitter current density for three hot electron triodes. The corresponding performance of the germanium transistor is also indicated.

COMPARISONS OF TRIODES

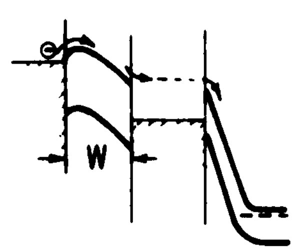
(1) NPN JUNCTION TRIODE



(2) TUNNEL EMITTER TRIODE



(3) SPACE CHARGE LIMITED EMITTER TRIODE



(4) SEMIC.-METAL EMITTER TRIODE (SMS)

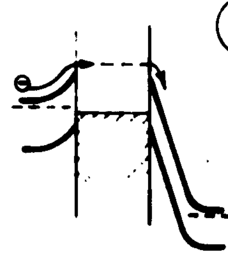
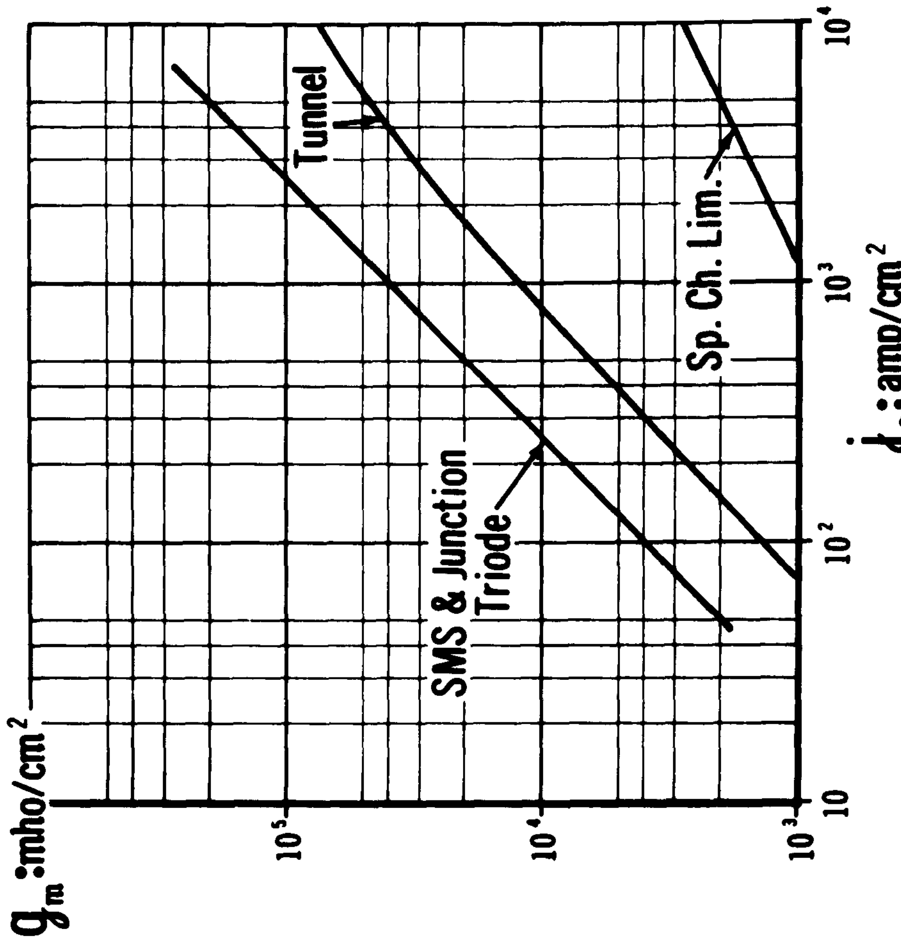


Figure 1



g_m :mho/cm^2
j_e :amp/cm^2
Tunnel
SMS & Junction Triode
Sp. Ch. Lim.
10
10^2
10^3
10^4
10^3
10^4
10^5

Figure 2

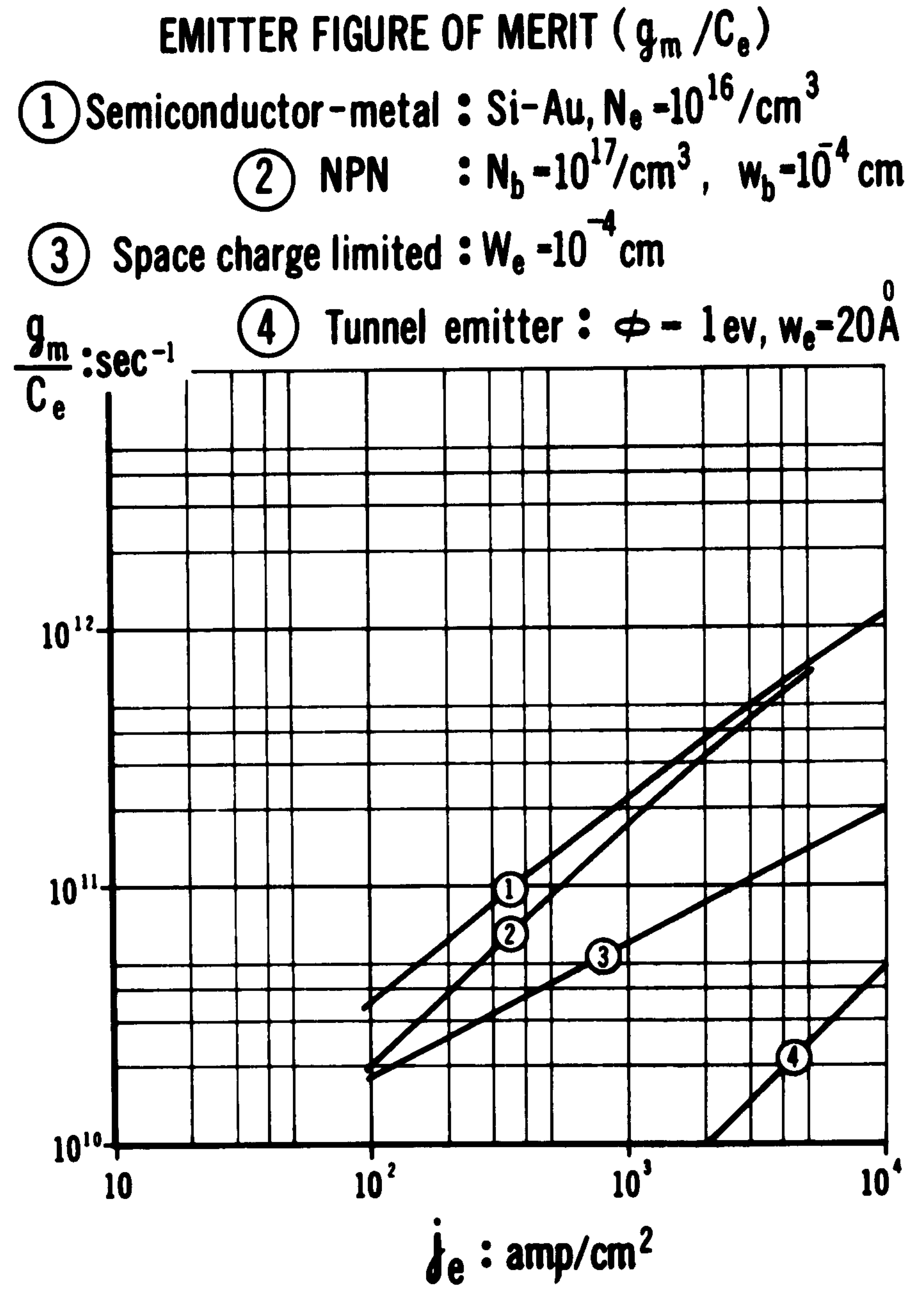
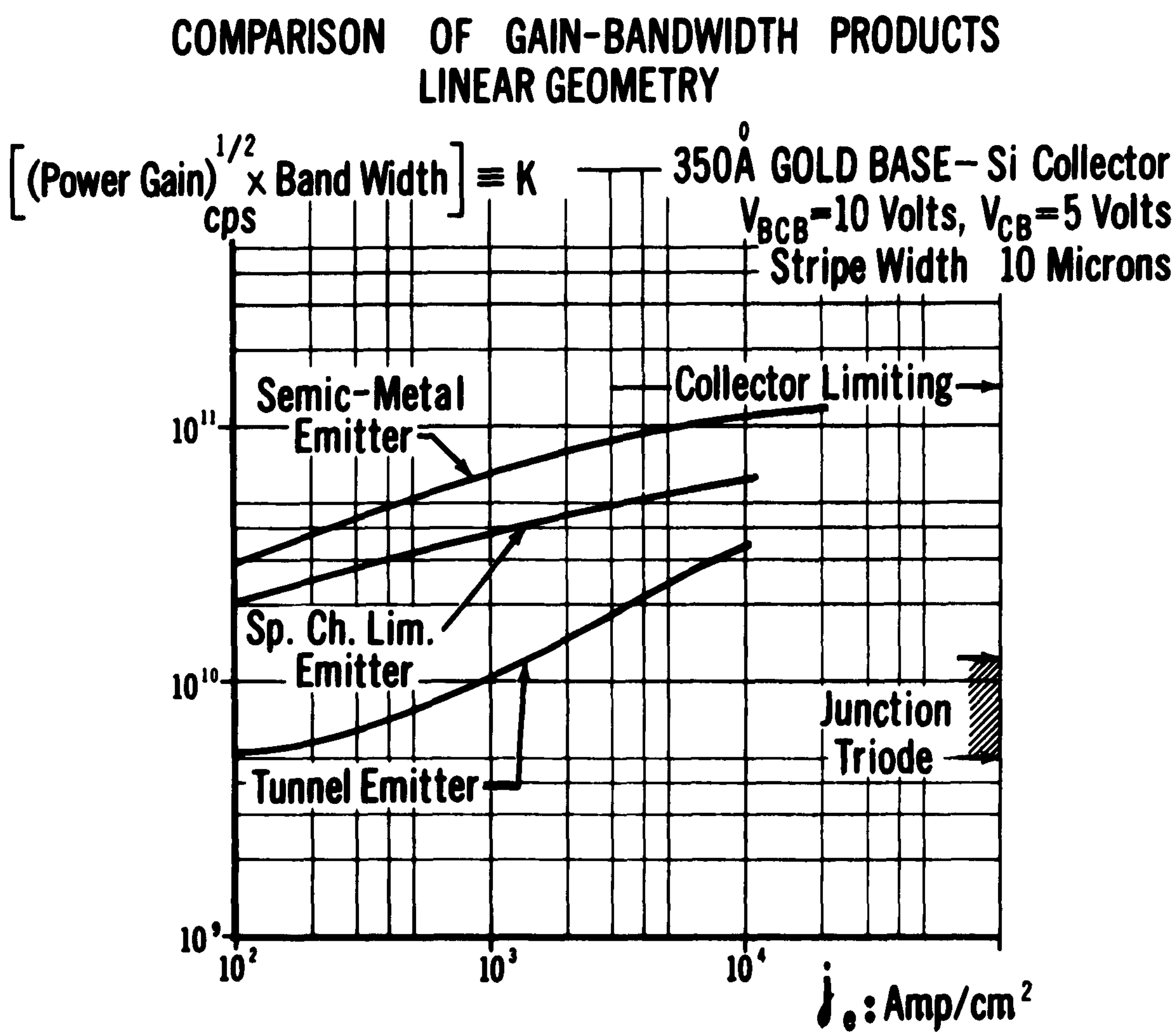

EMITTER FIGURE OF MERIT (g_m/C_e)
① Semiconductor-metal : Si-Au, N_e -10^{16}/cm^3
② NPN : N_b -10^{17}/cm^3, w_b-10^{-4} cm
③ Space charge limited : W_e -10^{-4} cm
④ Tunnel emitter : ϕ - 1ev, w_e=20$\mathring{A}$
$\frac{g_m}{C_e}$: sec^{-1}
10^{12}
10^{11}
10^{10}
10
10^2
10^3
10^4
1
2
3
4
j_e : amp/cm^2

Figure 3



COMPARISON OF GAIN-BANDWIDTH PRODUCTS
LINEAR GEOMETRY
[(Power Gain)^1/2 x Band Width] ≡ K
cps
350Å GOLD BASE – Si Collector
VBCB=10 Volts, VCB=5 Volts
Stripe Width 10 Microns
Collector Limiting
Semic-Metal
Emitter
Sp. Ch. Lim.
Emitter
Tunnel Emitter
Junction
Triode
10^11
10^10
10^9
10^2
10^3
10^4
je: Amp/cm^2

Figure 4

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Unclassified Report

Analysis is presented of the frequency performance of various metal-base hot carrier triode amplifiers which differ only in the type of hot carrier emitter they utilize. The triodes considered are: (1) The SMS, or semiconductor-metal-semiconductor, triode utilizing a Schottky barrier emitter; (2) The space charge limited emitter triode; and (3) The tunnel-emitter triode. The results are compared with the performance of the bipolar germanium junction transistor. It is shown that for all three hot carrier triodes, the maximum gain-band product increases with current density and approaches an assymptotic limit of about 1.4x10^8/S which is due to collector limitation, where S is the stripe width in cm. It is further shown, however, that this limit is closely approached at reasonable current density only by the SMS triode. This limit is to be compared with a value of (5 to 12) 10^6/S for the germanium transistor. At an emitter current density of 1000 amp^2/cm^2 and a stripe width of 10 microns, the maximum gain-band products, or maximum oscillating frequencies, are 60 kmc/sec for the SMS triode, 38 for the space charge limited emitter triode, and 10 for the tunnel-emitter triode.

1. Transistors
2. Diodes (Semi-conductor)
3. Semiconductors
4. Photoelectric Effect
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III. -hp associates-, Palo Alto, Calif.
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2. Diodes (Semi-conductor)
3. Semiconductors
4. Photoelectric Effect
I. AFSC Project 4608, Task 460804
II. Contract AF19 (628) 1637
III. -hp associates-, Palo Alto, Calif.
IV. Atalla, M.M.
V. In ASTIA collection

Electronic Research Directorate, Air Force Cambridge Research Laboratories, Bedford, Mass.
Rpt. No. AFCRL-62-957. INVESTIGATION OF HOT ELECTRON EMITTER; Scientific Report No. 2, Nov. 62. 12p., illus., 10refs.

Unclassified Report

Analysis is presented of the frequency performance of various metal-base hot carrier triode amplifiers which differ only in the type of hot carrier emitter they utilize. The triodes considered are: (1) The SMS, or semiconductor-metal-semiconductor, triode utilizing a Schottky barrier emitter; (2) The space charge limited emitter triode; and (3) The tunnel-emitter triode. The results are compared with the performance of the bipolar germanium junction transistor. It is shown that for all three hot carrier triodes, the maximum gain-band product increases with current density and approaches an assymptotic limit of about 1.4x10^8/S which is due to collector limitation, where S is the stripe width in cm. It is further shown, however, that this limit is closely approached at reasonable current density only by the SMS triode. This limit is to be compared with a value of (5 to 12) 10^6/S for the germanium transistor. At an emitter current density of 1000 amp^2/cm^2 and a stripe width of 10 microns, the maximum gain-band products, or maximum oscillating frequencies, are 60 kmc/sec for the SMS triode, 38 for the space charge limited emitter triode, and 10 for the tunnel-emitter triode.

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